AN OFFICIAL NACE PUBLICATION

A Reprint from
Materials
Performance

VOLUME 26 • FEBRUARY, 1987 • PAGES 23-28

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Advances in offshore cathodic protection modeling using the boundary element method*

R. Strommen, W. Keim,* J. Finnegan,** and P. Mehdizadeh***

Principles and practical aspects of offshore cathodic protection (CP) design have been reviewed for comparison. Additionally, a brief presentation of traditional methods for CP design analysis and CP criteria are discussed. This paper presents the capabilities of a computer program system for modeling CP using the Boundary Element Method (BEM). The program has capabilities for analyses of dynamic and temporal effects on the level of CP simultaneously and predicts the time dependent current density and potential behavior resulting from the formation of a calcareous deposit.

Introduction

WHILE METHODS FOR NUMERICAL ANALYSIS and computer modeling were developed into practical tools for structural engineers more than 20 y ago, similar developments date back only a few years in the field of corrosion and cathodic protection (CP).

Traditional CP design analysis procedurse, using a few simple formulas combined with rules of thumb, are still the dominate means for estimating anode numbers and distributions. However, over the last few years there has been an increasing interest in the development of computer modeling techniques for electrochemical systems and particularly for applications in offshore CP. This trend has been related to the increased activity worldwide in deepwater offshore drilling and production of oil and gas. Large offshore structures of increasing size and complexity have been installed in still deeper waters and in hostile environments. This increased complexity in combination with uncertainty in CP design parameters has resulted in a large number of examples of structures of unsatisfactory CP performance. This situation has produced a need for more adequate and reliable methods for design of CP systems. The computer programs recently developed have proved very useful for troubleshooting of existing structures, design analysis of sacrificial and impressed current systems, checking for interference effects, and processing of CP potential and electric field gradiant/current density readings obtained on platforms and pipelines. In turn, this activity has provided a vast amount of accurate current density vs potential data, subsequently used as boundary conditions in the computer programs.

The first computer programs using such numerical techniques, developed for offshore CP design analysis, were probably those developed by one of the authors in the 1970s, which were based on the Finite Difference Method (FDM).[1-4] Since then a considerable number of papers have been presented describing programs and capabilities based on numerical techniques such as the FDM, FEM (Finite Element) and BEM (Boundary Element Method). The BEM is now becoming the most popular among the methods noted, because of certain advantages over other methods.[5-11] Examples presented here are mainly obtained using a new, advanced BEM-based CP Modeling package. This system was developed for Conoco Norway Inc. by CorrOcean a.s. in cooperation with Compmech Ltd. (UK), Fegs Ltd. (UK), and Conoco Norway Inc.

Background

Corrosion of steel in seawater occurs by a mechanism that involves at least two reactions. The anodic reaction, which is dissolution of iron, is written as:

$$Fe = Fe^{++} + 2e \tag{1}$$

The rate of this reaction and, therefore, the corrosion rate can be expressed as a current density, i_{corr} (mA/m^2), and is determined by the cathodic reaction rate that normally is oxygen reduction:

$$1/2\,O_2 + H_2O + 2e = 2OH^- \tag{2}$$

For corroding steel in seawater [i.e., at the corrosion potential (E_{corr})], these two reactions balance each other. All electrons produced by the anodic reaction are consumed by the cathodic reaction. (Possible hydrogen evolution has been neglected.)

Corrosion and reaction rates depend on the electrochemical potential of steel in seawater. If the potential is reduced to a level called the reversible potential, E_o (steel) or lower, the reaction is subsequently increased.[2] Such reductions in potential are achieved in practice using CP, either by sacrificial anodes or by an impressed current system.

Figure 1, shows in principle, the reaction rates on the steel and on the sacrificial anodes vs potential. The potentials of the steel become more negative and the potentials of sacrificial anodes become more positive, balancing somewhere between the open circuit potentials of the two different metals. Provided an adequate CP design, a high quality anode

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*Presented during CORROSION/86, Paper No. 45, NACE, Houston, TX, 1986.

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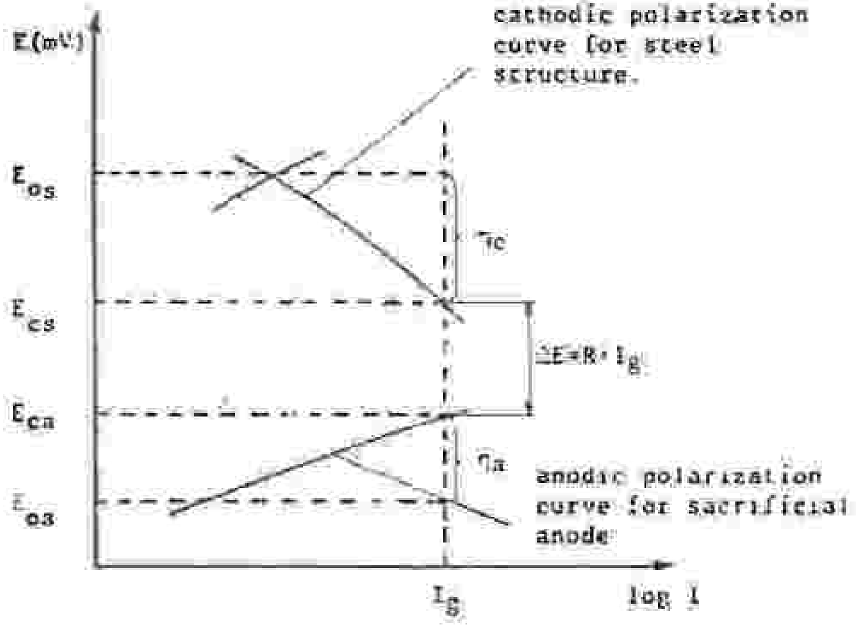

FIGURE 1 — Polarization diagram for a protected steel structure with sacrificial anode(s). E_{os} = open circuit (corrosion) potential of steel structure; E_{cs} = open circuit (corrosion) potential of anode; E_{ca} = closed circuit potential of anode; η_c = (cathodic) polarization of structure on galvanic coupling to sacrificial anode; η_a = (anodic) polarization of anode on galvanic coupling to the steel structure; I_g = galvanic current = I_a = I_c — The figure η_a/I_a, i.e., polarization of the anode, should be as low as possible; and $\Delta E = R \cdot I_g$ = voltage drop in the seawater between the anode(s) and the structure. ΔE is a function of location (i.e., of coordinates x, y, z).

will polarize only a few millivolts while the steel surface can polarize 300 to 500 mV or more into the protected range.

Traditional design procedures for CP systems involve the calculation of anode current output applying Ohm's law:

$$I = \frac{\Delta E}{R} \tag{3}$$

where:
ΔE = "the driving force"
R = ohmic resistance.
I = current output from anode.

The driving force for a sacrificial anode design ΔE is equal to the total IR-drop in the seawater between the anode and the protected structure, normally defined as the difference between the protection potential of steel, E_{prot}, and the closed circuit potential of the anode, E_{anode} (Figure 1).

Ideally, the ohmic resistance ΔR includes the following elements:

$$R = R_a + R_c + R_m \tag{4}$$

where:
R_a = anode-to-electrolyte resistance or simply "anode resistance."
R_c = cathode (or steel structure)-to-electrolyte resistance, and
R_m = any metallic resistance(s) in the structure, (i.e., cables) between anode and cathode.

The two latter elements of Equation (5) (i.e., R_c and R_m) are usually considered negligible. There is strong evidence from offshore measurements that the contribution represented by R_c is considerable. This element refers to potential distribution over the protected structure and may be quite high locally at complex nodes, at pile guides and pile sleeves, etc. However, while the anode resistance may be calculated using basic and simple methods and formulas, this is not the case for R_c. Advanced computer modeling utilizing methods as noted is the answer to this problem. Problems and errors mentioned have been accepted when using the traditional design procedures, and have been compensated for by using solid safety factors. Thus, the anode current output is calculated applying the following equation:

$$I_a = \frac{\Delta E}{R_a} \tag{5}$$

where:
I_a = anode current.
$\Delta E = E_{prot} - E_{anode}$.
R_a = anode resistance.

The anode resistance is obtained using a formula that includes the seawater/electrolyte resistivity and parameters defining the anode geometry.

Design criteria

Steel is protected against corrosion in seawater when polarized to −800 mV vs the Ag/AgCl/seawater reference electrode. Under conditions where there is a danger for corrosion fatigue, overprotection with hydrogen evolution may also represent a problem. Potentials down to −1050 mV vs Ag/AgCl/seawater are considered safe except for the high strength steels.

For sections of steel structures buried in mud, the anaerobic conditions create a hazard for SRB (sulfate reducing bacteria) corrosion. It is normally anticipated that a potential of −900 mV vs Ag/AgCl is required to reduce the corrosion to an acceptable level under such conditions.

The current density required per square meter to polarize steel to a protective potential level, defines the number of anodes required, regarding output capacity as well as to satisfy the total amount of electricity (A·h) required throughout the life of the structure. Table 1 shows the current density requirements for different geographical areas reproduced from DnV codes.

Modeling utilizing the BEM

The electrostatic potential (ΔE) reflecting the flow of electric current in the seawater from anodic to cathodic sites, obey the Laplace equation:

$$\nabla 2 E = 0 \tag{6}$$

TABLE 1 — Guidance on minimum design current densities (mA/m²) for CP of bare steel

	Initial value	Mean value	Final value
North Sea (northern)	160	120	100
North Sea (southern)	130	100	90
Arabian Gulf	120	90	80
India	120	90	80
Australia	120	90	80
Brazil	120	90	80
Gulf of Mexico	100	80	70
West Africa	120	90	80
Indonesia	100	80	70
Pipelines (burial specified)	50	40	30
Risers in shafts with flowing seawater	180	140	120
Risers in shafts with stagnant seawater	120	90	80
Saline mud (ambient temperature)	25	20	15

Calculation of the potential and current density distributions over the surfaces of a protected structure involves the solution of this equation for adequate boundary conditions. In addition to definition of the geometry, such boundary conditions must comprise equations or data describing the relationship between potential and current density for the anodic and cathodic surfaces. The current density must furthermore satisfy the relationship:

$$i = -\delta \frac{\partial E}{\partial n} \tag{7}$$

where:
i = current density.
∂ = conductivity of the electrolyte (seawater).
n = normal to the surface area in question.

Previously, numerical methods like the FDM and FEM have been more commonly used. Over the last few years, however, the BEM has been developed to a level whereby it may be used with great advantage for CP modeling. Most examples presented below have been obtained using a program system that includes a BEM-based analysis module.

Following Brebbia, et al., the boundary element method yields the following fundamental matrix equation for a homogeneous system:[12,13]

$$\underset{\approx}{H}\,\underset{\approx}{E} = \underset{\approx}{G}\,\underset{\approx}{q} \tag{8}$$

where H and G are denoted influence matrices, and E and q are potential and field normal to surface elements, respectively. (E may be added as a constant depending on which reference electrode the potential is referred to.) For constant elements, the matrices H and G are defined for an element number i relative to element j by the surface integrals as follows:

$$H_{ij} = \frac{-\overrightarrow{r_{ij}}\,\overrightarrow{nj}}{4\pi} \iint \frac{1}{r_{ij}^{3}}\,dS_j \tag{9}$$

$$G_{ij} = \frac{1}{4\pi} \iint \frac{1}{r_{ij}}\,dS_j \tag{10}$$

where:
$\overrightarrow{r_{ij}}$ = the radius vector from element i toward element j.

$\overrightarrow{nj}$ = the normal vector to element j.

For a three-dimensional system, the boundary elements are plane or curved surface elements, allowing for a great reduction in the size of the numerical problem, compared to the FDM and FEM Methods. Using plane and curved surface elements and tubular elements, the program system has proved an excellent tool for modeling, not only sections of a platform, but complete, large-size platforms of considerable complexity.

The analysis may be completed by the use of a global model of the whole structure, or comprise modeling of a local section following a set-up as follows:

1. Global modeling of a large, complex structure using tubular BEM elements.
2. Studying local distributions and effects by "zooming in" on a critical section like a node or a pile guide area of a structure using surface elements (Figure 2).

Advantages using BEM are first and foremost:

1. Reduction in size of the numerical problem, making it possible and economical to model large and complex structures.
2. Combined with a user-friendly, interactive-mesh generator, the time and efforts required for establishing the model geometry are strongly reduced.
3. Infinite problems are easy to handle.

Since the conductivity has to be constant throughout the regime that is modeled, it is possible to handle layers of different conductivity by splitting the problem into different zones, solving the problem within each such regime separately, and matching the solutions at the boundaries.

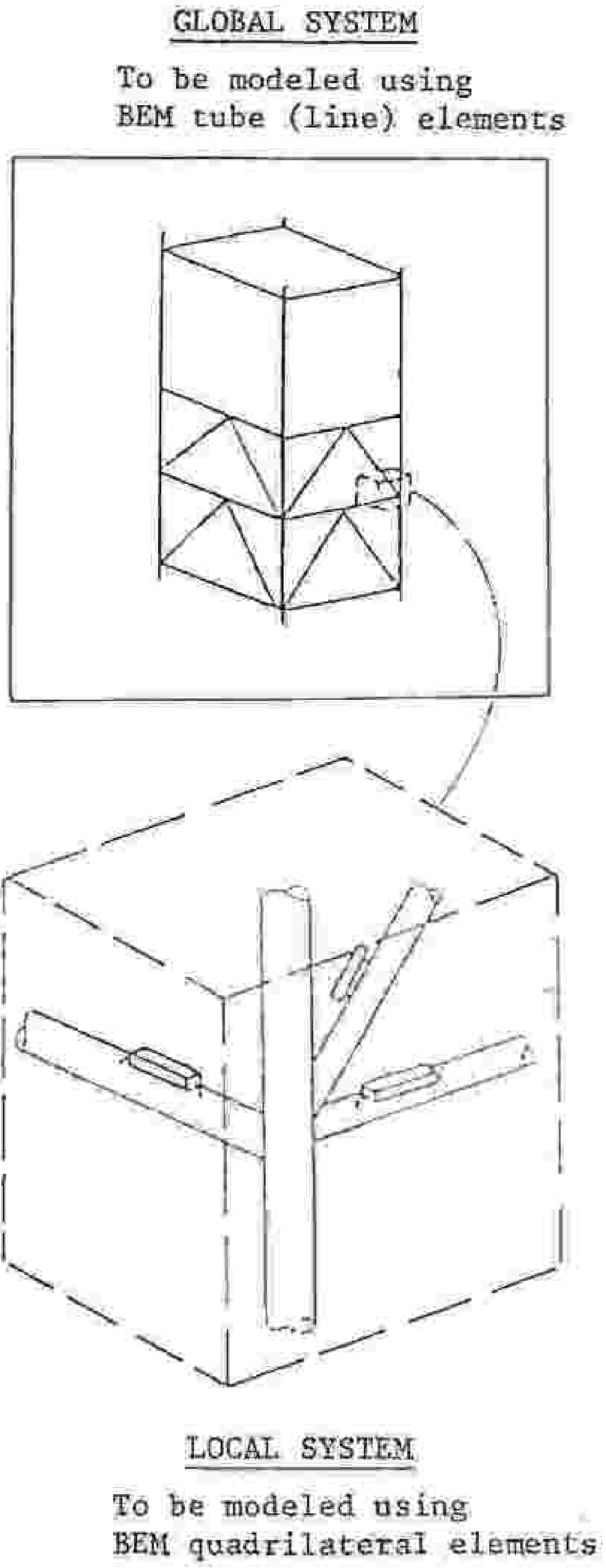

FIGURE 2 — Showing the principle of using global and local models: the first gives the general solution to the problem, and the latter shows the detailed distributions locally.

Behavior of exposed steel and anodes in seawater

The boundary conditions to be applied in the program, in addition to structural geometry and electrolytic conductivity, are defined by the electrochemical properties of the cathodes and anodes in seawater, and in mud if buried.

The electrochemical behavior of these materials (anodes and cathodes) creates a complex potential-current density relationship, which varies with the environmental parameters, such as salinity, pH, oxygen concentration, temperature, and

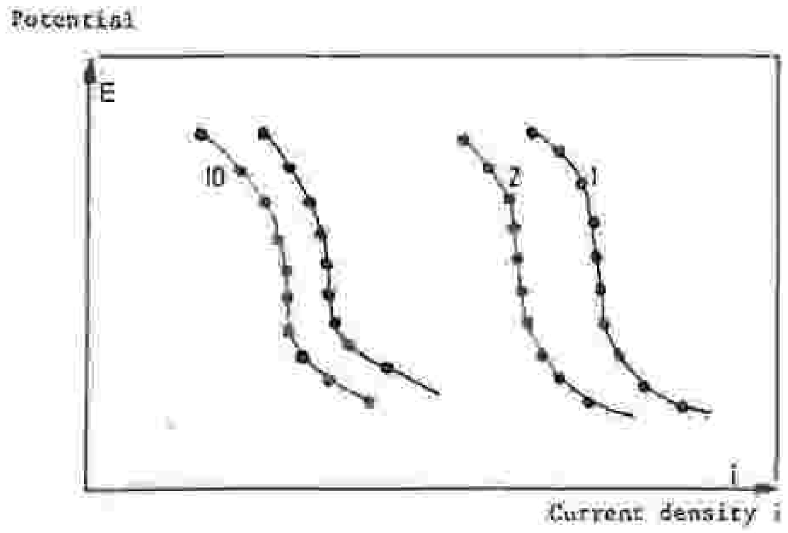

FIGURE 3 — The Basic Data File contains polarization curves reflecting changes in the quality of the calcareous coatings with time for one set of environmental conditions.

flowrate. Aging is another important dynamic parameter. The aging effect is the result of the formation of a calcareous layer upon the cathode, under satisfactory conditions of CP. This aging parameter is defined in terms of the material and electrochemical and environmental parameters as a function of time. This time-dependent (dynamic) behavior creates the unique potential (current density) time relationship, which accurately describes the "state-of-the-system" for all situations. The aging effect systematically records the local and global effects of sufficient or insufficient CP and predicts the future potential and current density levels on the structure.

The aging effect depends on the history of variation in the parameters listed above for each individual surface element. This may also include scouring and other incidents of damage to coatings. Theoretical models alone are obviously not satisfactory for establishing a reliable procedure for handling such aging processes. An extensive database, together with a procedure, has been established for modeling the real process of aging of cathodically protected steel in seawater and of typical sacrificial anode alloys. The database has been collected (i.e., through large-scale seawater tests and mainly through in-situ CP and current density measurements on a large number of offshore steel structures).

The corrosion behavior of exposed steel in seawater (i.e., the reaction kinetics) are described as potential vs current density relations, normally denoted polarization curves. Depending on the aim of the calculation, the boundary conditions may be modeled at different levels of increasing complexity:

1. Constant current density.
2. Linear relation between current density and potential.
3. Time dependent nonlinear polarization curves.

The "level 3" complexity is required to model aging effects as described above.

Digitized potential and current density values may describe the polarization curve for any empirical measured condition, reflecting surface coating quality and environmental conditions in the seawater.

A set of such curves, stored in a Basic Data File, also reflects different levels of aging of the surface (Figure 3).

Any of these curves represent an instantaneous change in current density for a given change in potential for a steel surface element of a given history (i.e., with a specified quality of the calcareous coating). While curve No. 1 in this set represents a fresh or newly exposed surface, curve No. 10 represents a completely "polarized" condition (i.e., characterized by a fully developed calcareous coating). Intermediate curves represent intermediate stages defined by time after start-up, and previous variation in current density, potential, and environmental parameters.

The Basic Data File includes curves for different flow rates, temperature levels, salinity, and oxygen concentrations. Polarization curves for sacrificial anodes are treated in a similar manner. Tests of the accuracy of the programs and models have been carried out for a large number of static conditions (e.g., of complex platform nodes, with excellent agreement between calculations and measurements). Initial tests have also demonstrated good agreement between measurements offshore and calculations involving the time dependent, dynamic aging processes.

Applications and results

Because of the size of the problems, involving models with several thousands of elements, efficient presentation of the results are done graphically. The postprocessor used has the following capabilities:

1. Two- and three-dimensional plots of structural segments with anodes.
2. Iso-potential and iso-current density plots.
3. Potential profile and CD profile plots.
4. Checks vs codes and recommended practices.
5. Restart capabilities.

Examples of applications and results have been presented in Figures 4 to 8.

The examples comprise modeling of large platforms with

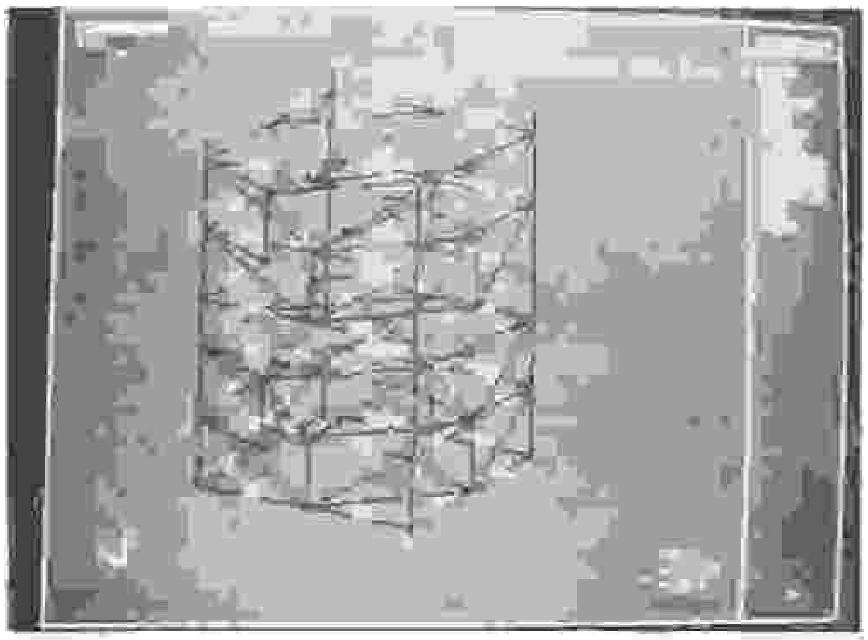

FIGURE 4 — Graphic plot of a global model of a platform with sacrificial anodes.

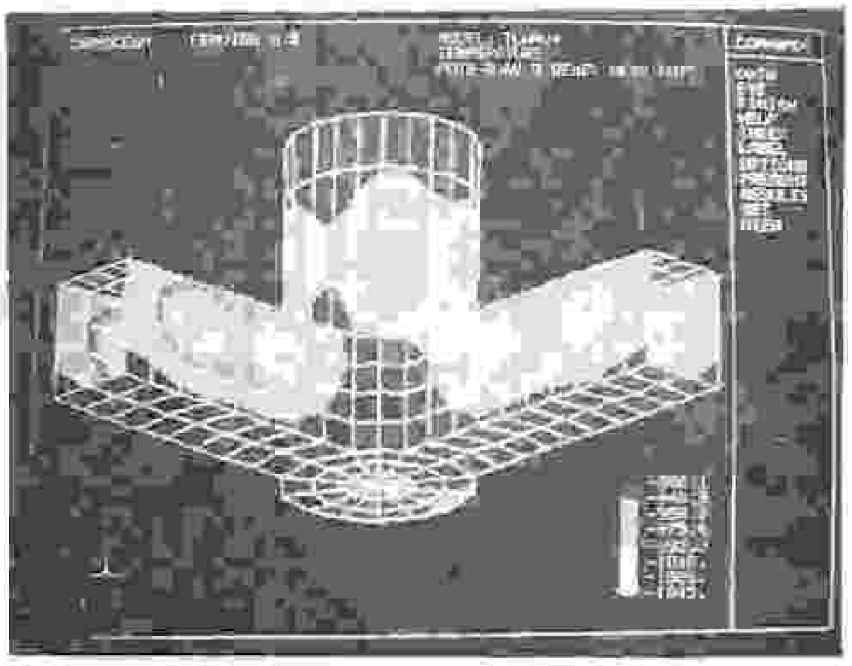

FIGURE 5 — Graphic plot of potential distributions for a large section of a floating structure with impressed current anodes.

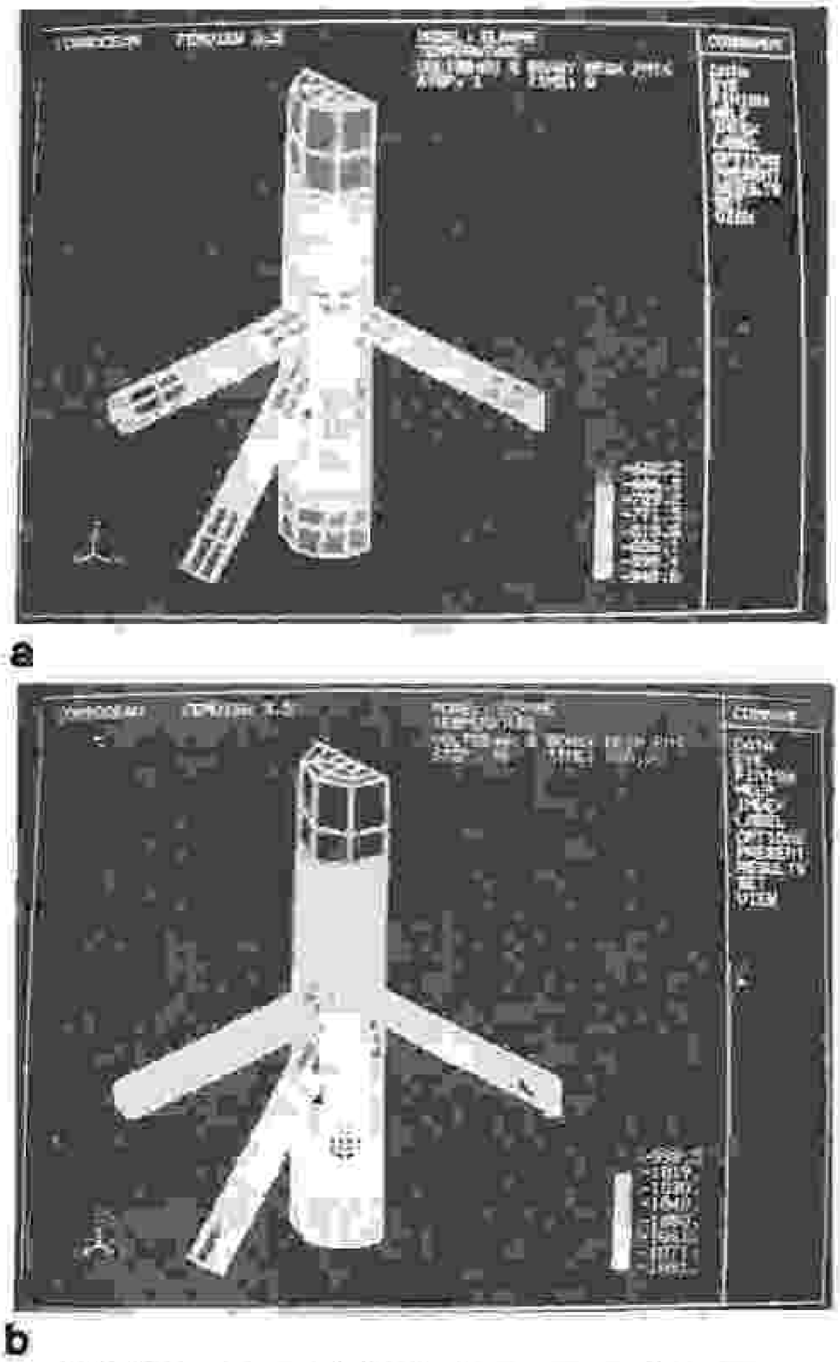

FIGURE 6 — Potential distribution over a node corner of a platform with bracelet anodes, shown: (A) for time step 1 immediately after launch, and (B) at time step 30 after 300 days.

sacrificial anodes using a global model based on tubular elements (Figure 4), and a large section of a simpler floating structure with impressed current anodes (Figure 5), using surface elements. The next example (Figure 6) includes a nodal area for a platform using bracelet anodes. The potential distributions have been presented for time zero (launch) and 300 days after start-up (i.e., before and after adequate polarization of the structure).

The change with time in polarization of this nodal area reflects the aging process with formation of calcareous deposits on the steel. This dynamic aging process is even more clearly demonstrated in Figure 7 where shading has been used to show the "spread of protection" with time for a bottle leg area with pile sleeves. (Colors can be used to show these changes more dramatically.)

One other application that has proved useful over the last 4 to 5 y has been the processing of potential and electric field gradient readings, obtained in-situ on the offshore structures. Figure 8 shows a curve fitting used to estimate current output from sacrificial anodes.

Readings of this type have proven a need for revision of the traditional CP design procedures as well as of design parameters for the North Sea.

Summary

The main areas of application of computer modeling in offshore CP are as follows:

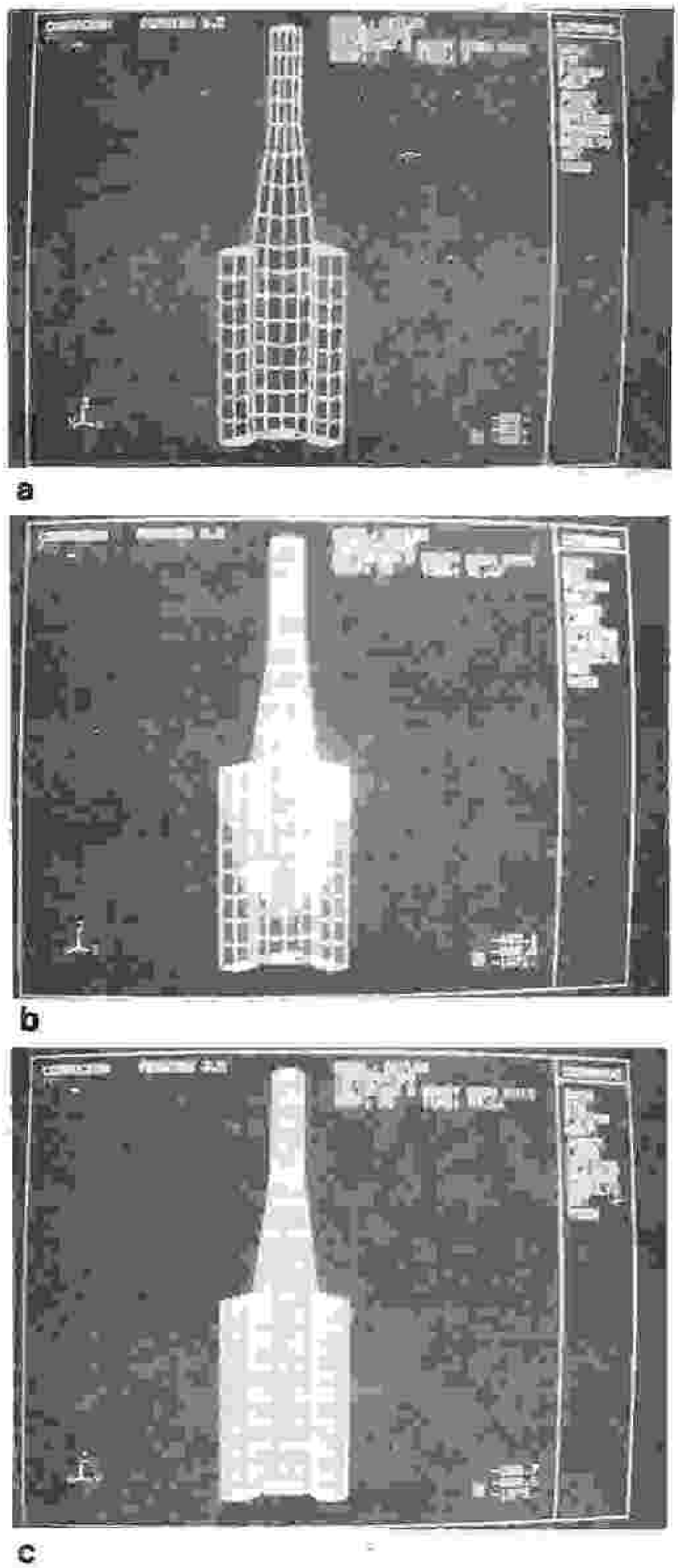

FIGURE 7 — Demonstration of the dynamic aging process causing a gradual polarization of the structure. To demonstrate this effect shading has been used: unshaded for unprotected areas and shaded for sections polarized to −800 mV or more negative vs Ag/AgCl reference electrode: (A) The potential in mV vs Ag/AgCl immediately after launching shows that the structure is still unprotected (unshaded); (B) After 23 days of exposure, roughly half of the structure is protected (partly shaded); (C) A full protection is reached after 94 days (all shaded).

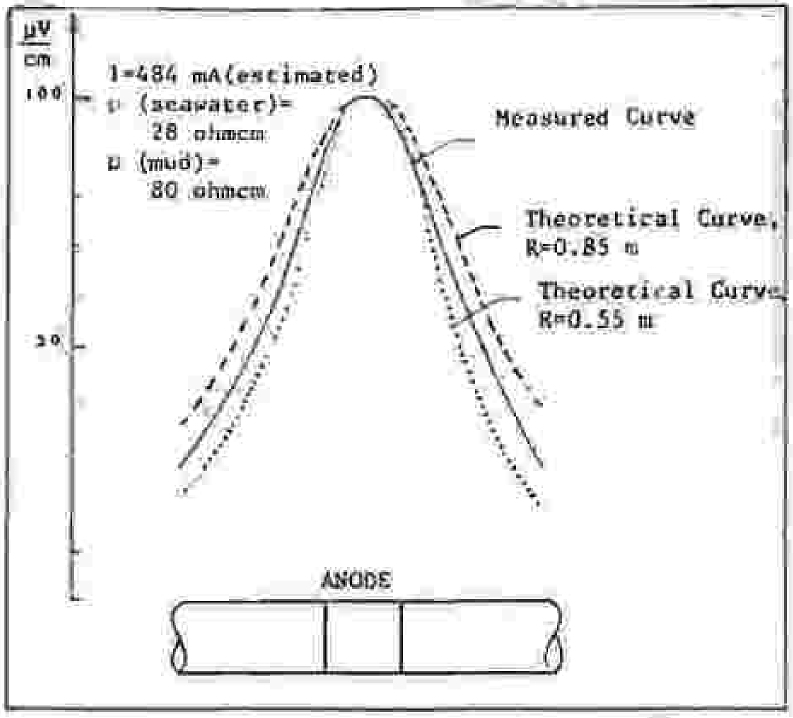

FIGURE 8 — Computer models are utilized to obtain field gradient curves (e.g., at bracelet anodes). By curve fitting of measured profiles to the modeled curves, exact information on anode output is obtained. (R = radial distance from the pipe.)

1. CP design analysis for new structures, such as optimization of anode size, number, and distribution by modeling over the life of the structure: Included in the design analysis is the study of possible shadow effects in geometrically complex sections of the platforms, and possible interference effects between platform, risers, and pipelines.

Application of the program may be particularly useful for structures of new designs or of increased size or complexity compared to previous projects, for which no data are available to the design engineer based on previous experience. The same applies when going into a new geographical area for which the environmental conditions may vary compared to previous experience.

2. Troubleshooting by analysis and redesign of CP systems for existing under-protected structures: Modeling an existing CP design and matching the results with measured potentials, a proposed redesign is checked by adding the suggested type and number of anodes in the model, and it will be demonstrated whether this is satisfactory or not to cure the problem. Through trial and error, the modeling will demonstrate the optimal number and positions of anodes to bring the potential level back to the required value.

3. Processing of potential and field gradient readings obtained in-situ on the structures to disclose performance data (current density vs potential) for the CP systems and, thereby, also causes for possible problems: Such applications have recently demonstrated a need for revision of design methods and criteria for offshore CP.[14]

4. Study of CP and training of CP engineers by using the program as a training simulator. Training simulation programs typically may include study of the aging process for cathodically protected steel and the dynamics in distribution and redistribution of potentials and current densities.

5. The models may be used for comparison of alternative systems and CP designs, including the development of new types of anodes and their geometries. In this context, it is also used to calculate anode resistance values as used in the more basic analysis procedures described above.

Acknowledgment

The authors would like to thank Conoco Norway, Inc. for support and cooperation on this project and for permission to publish this material.

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